B_s oscillations

Massimo Casarsa

FNAL, USA

for the CDF and DØ Collaborations

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Overview

- For many years the B_s-$\bar{B}_s$ system had eluded a complete investigation of its observables. Only recently the Tevatron experiments have accumulated sizable B_s samples, which allow to study the system properties in detail.

- This talk will overview the most recent and outstanding measurements of the B_s-$\bar{B}_s$ system parameters by CDF and DØ experiments.

- <u>Talk outline:</u>
  - overview of the B_s-$\bar{B}_s$ system;
  - brief description of the experimental apparatus: the Tevatron and the CDF and DØ detectors;
  - observation of B_s oscillations and Δm_s measurement (new measurement by DØ);
  - Γ_s, $\Delta\Gamma_s$ and ϕ_s measurements (new measurement by CDF and new constrained combined result by DØ);
  - summary.

B_s^0-$\bar{B}_s^0$ system

- B_s mesons are $\bar{b}s$ bound states, which, like B_d, D and K neutral mesons, exhibit particle-antiparticle oscillations due to the flavor changing weak interactions.

- B_s-$\bar{B}_s$ time evolution is described by a 2×2 complex effective Hamiltonian, M - iΓ/2:

$$i\frac{\partial}{\partial t}\begin{pmatrix} B^0 \\ \overline{B^0} \end{pmatrix} = \begin{pmatrix} M - \frac{i}{2}\Gamma & M_{12} - \frac{i}{2}\Gamma_{12} \\ M_{12}^* - \frac{i}{2}\Gamma_{12}^* & M - \frac{i}{2}\Gamma \end{pmatrix}\begin{pmatrix} B^0 \\ \overline{B^0} \end{pmatrix}$$

- Mass eigenstates are a linear combination of flavor eigenstates:

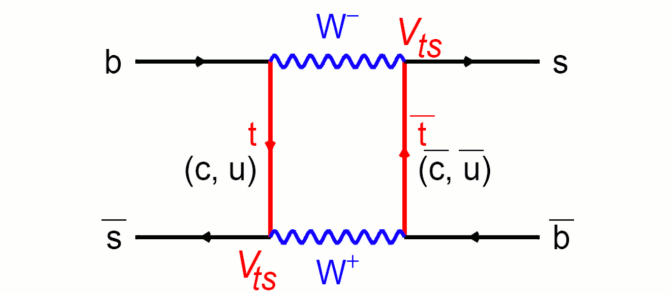
$$|B_{\mathrm{H}}\rangle = p\,|B_{\mathrm{s}}\rangle + q\,|\bar{B}_{\mathrm{s}}\rangle$$
$$|B_{\mathrm{L}}\rangle = p\,|B_{\mathrm{s}}\rangle - q\,|\bar{B}_{\mathrm{s}}\rangle$$

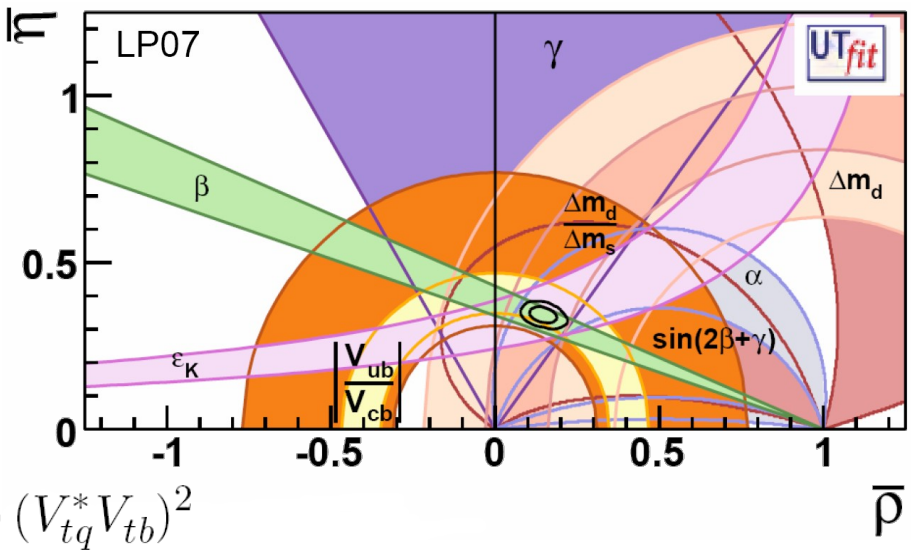
- B_s-$\bar{B}_s$ oscillations involve three physical quantities:

$$\Delta m_s = \mathrm{M_H} - \mathrm{M_L} = 2\,|\mathrm{M}_{12}|$$
$$\Delta\Gamma_s = \Gamma_{\mathrm{L}} - \Gamma_{\mathrm{H}} = 2\,|\Gamma_{12}|\,cos\,\phi_s$$
$$\phi_s = arg(-\mathrm{M}_{12}/\Gamma_{12})$$

B_s^0-$\bar{B}_s^0$ system in the SM

- In the Standard Model the $B_s \leftrightarrow \bar{B}_s$ transitions are described at lower order by W-exchange box diagrams:





$$M_{12} = -\frac{G_F^2 m_W^2 \eta_B m_{B_q} B_{B_q} f_{B_q}^2}{12\pi^2} S_0(m_t^2/m_W^2)\,(V_{tq}^* V_{tb})^2$$

$$\Gamma_{12} = \frac{G_F^2 m_b^2 \eta'_B m_{B_q} B_{B_q} f_{B_q}^2}{8\pi} \times \left[(V_{tq}^* V_{tb})^2 + V_{tq}^* V_{tb} V_{cq}^* V_{cb}\, \mathcal{O}\left(\frac{m_c^2}{m_b^2}\right) + (V_{cq}^* V_{cb})^2\, \mathcal{O}\left(\frac{m_c^4}{m_b^4}\right)\right]$$

- Recent SM calculations (A.Lenz and U.Nierste, hep-ph/0612167):

$$\Delta m_s = (19.3 \pm 6.7)\ \mathrm{ps}^{-1}$$

$$\Delta\Gamma_s = (0.088 \pm 0.017)\ \mathrm{ps}^{-1}$$

$$\phi_s = (4.2 \pm 1.4) \times 10^{-3}$$

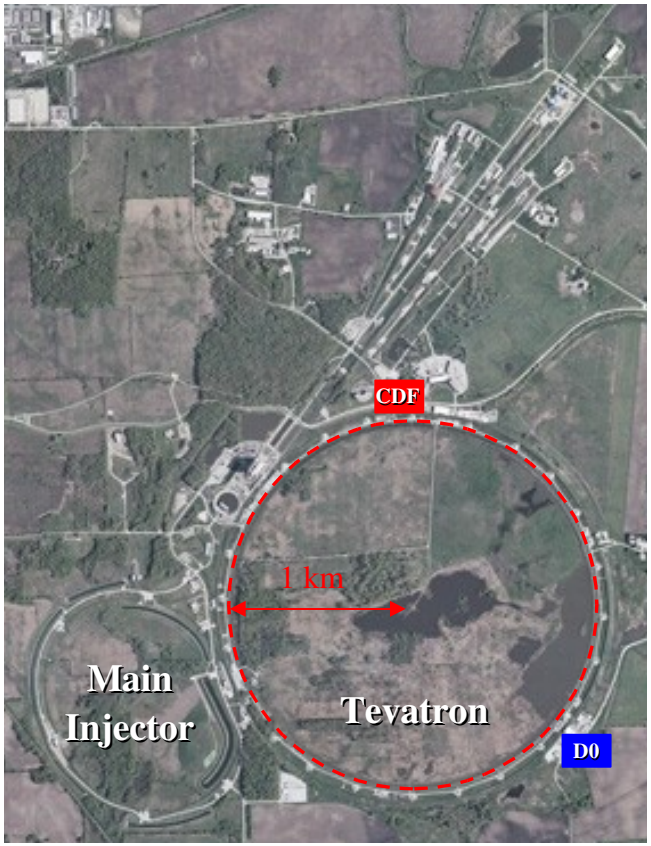
- Many uncertainties cancel in the ratio:

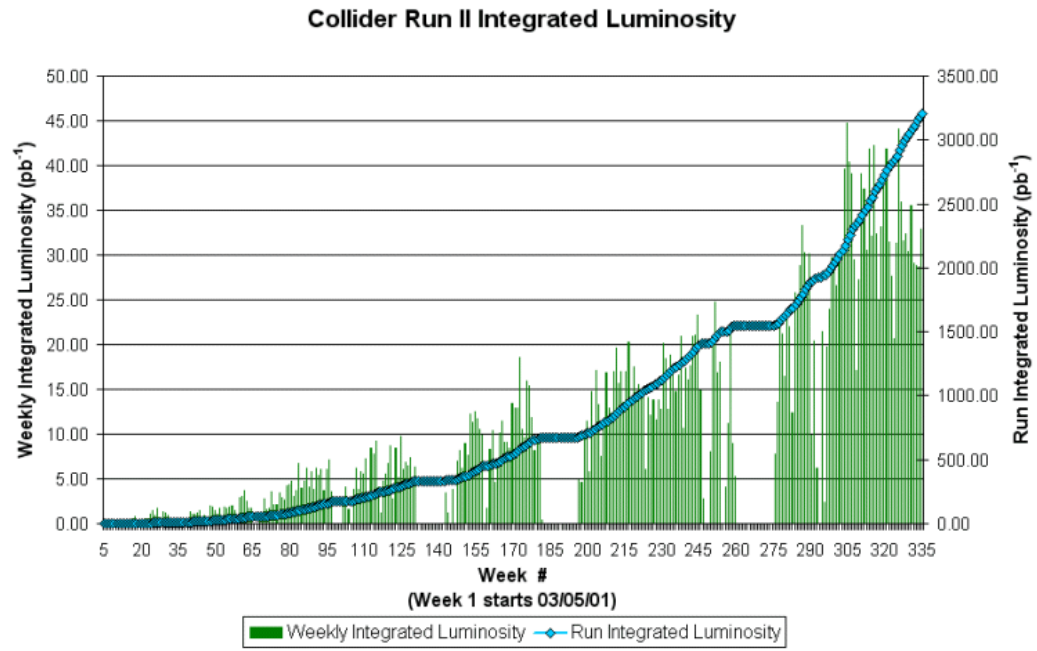
$$\frac{\Delta m_s}{\Delta m_d} = \frac{m_{B_s}}{m_{B_d}} \xi^2 \frac{|V_{ts}|^2}{|V_{td}|^2}$$

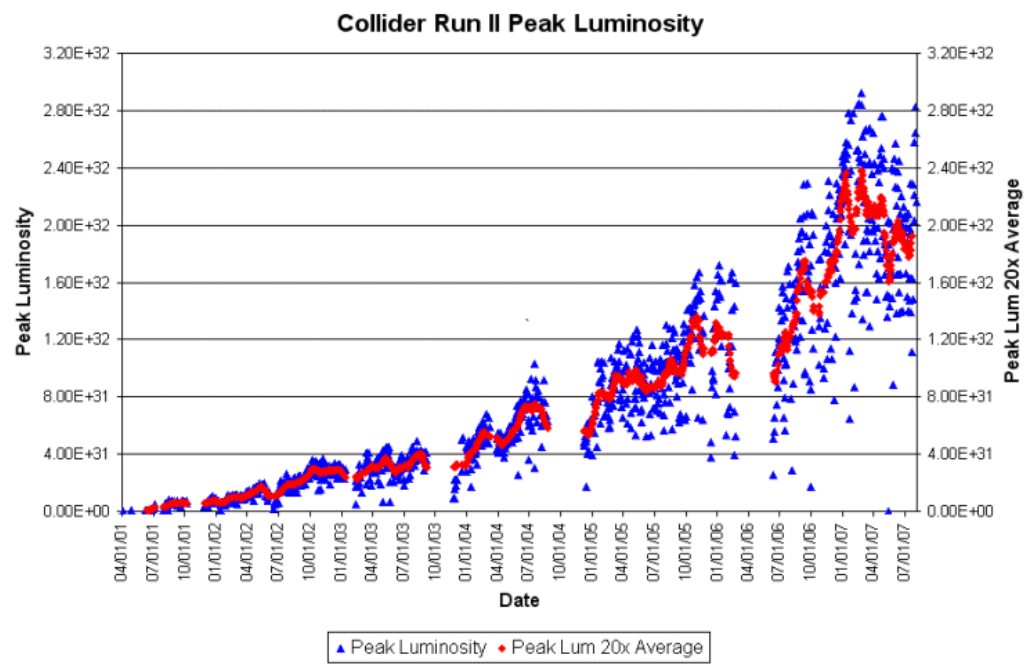
from lattice QCD: $\xi = 1.21^{+0.047}_{-0.035}$

(M.Okamoto, hep-lat/0510113)

Tevatron performance



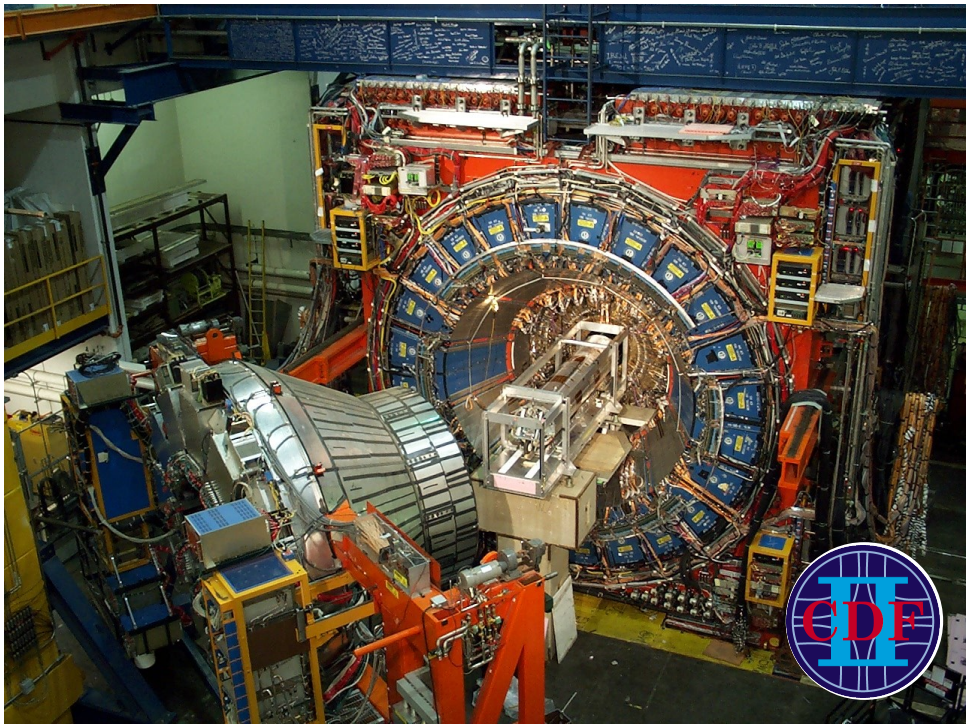


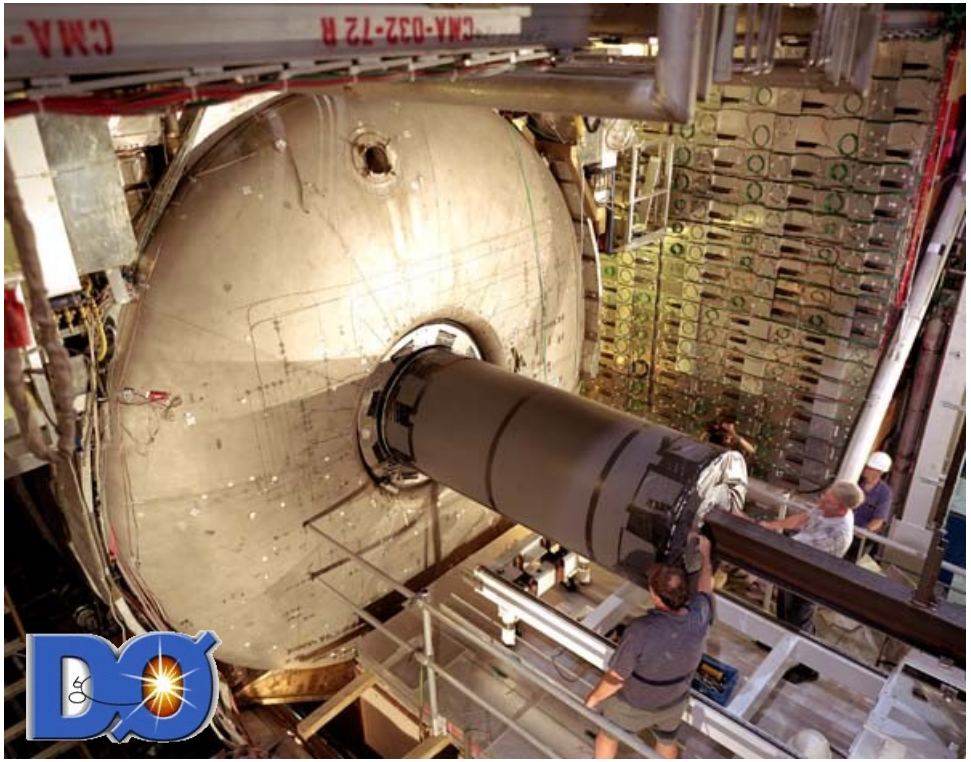


- p-$\bar{p}$ collisions at 1.96 TeV;
- peak luminosity ~2.9 $\times 10^{32}$ cm^{-2}s^{-1};
- weakly integrated lum. ~45 pb^{-1};
- ~3.3 fb^{-1} delivered per experiment (~2.8 fb^{-1} on tape).

Tevatron detectors

- CDF and DØ are multipurpose central detectors:
  - silicon microvertex detectors;
  - central tracking in magnetic field;
  - EM and hadronic calorimeters;
  - muon systems.





- DØ:
  - excellent muon coverage and ID;
  - tracking up to $|\eta|<3$;
  - new silicon Layer 0.
- CDF:
  - particle ID (ToF and dE/dx);
  - excellent mass resolution;
  - displaced track trigger at L2.

Δm_s measurement

Δm_s measurement overview

- Time-dependent measurement: detect an oscillatory pattern in proper time distribution of B_s decays:

$$P(t)_{B^0\to B^0} = \frac{1}{2\tau}e^{-t/\tau}(1+\cos\Delta m t)$$
$$P(t)_{B^0\to \overline{B^0}} = \frac{1}{2\tau}e^{-t/\tau}(1-\cos\Delta m t)$$

- Three ingredients:

$$\text{Sig} = \sqrt{\frac{S\epsilon D^2}{2}}\, e^{-\frac{(\Delta m_s \sigma_t)^2}{2}} \sqrt{\frac{S}{S+B}}$$

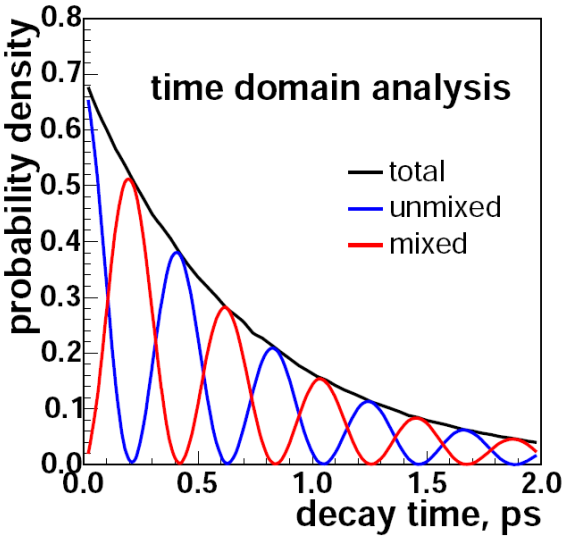
tagging efficiency

dilution = 1 – 2 × (mistag probability)

proper time resolution

signal

background

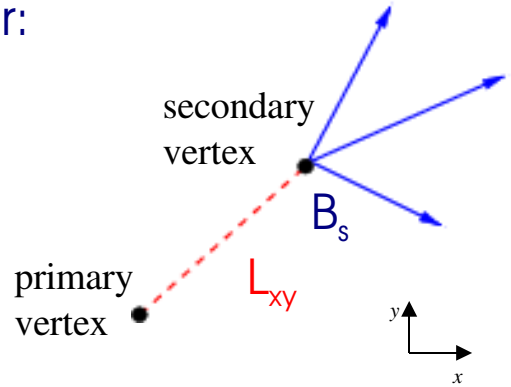


❶ Measurement of B_s decay flavor: inferred from B_s decay products;

❷ measurement of B_s production flavor: flavor tagging techniques;

❸ proper decay time measurement:

$$ct = L_{xy}\frac{m_B}{p_T(B)}$$

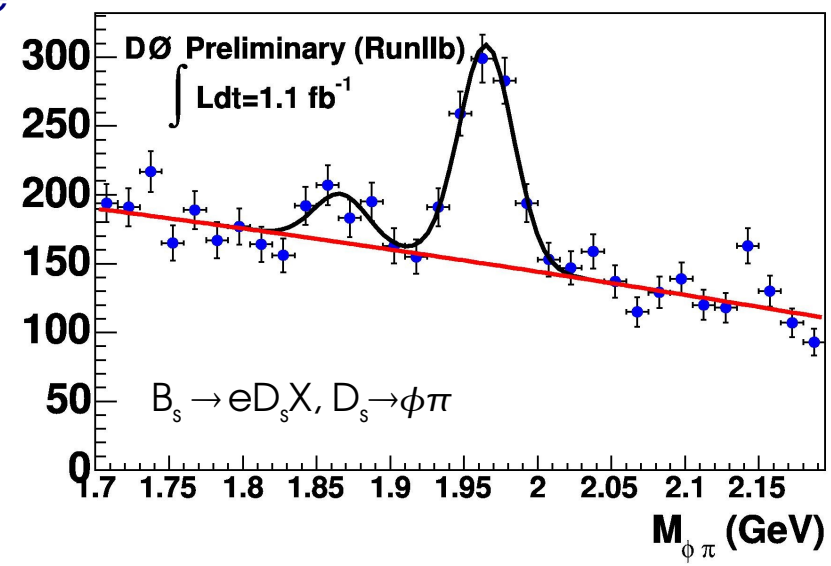


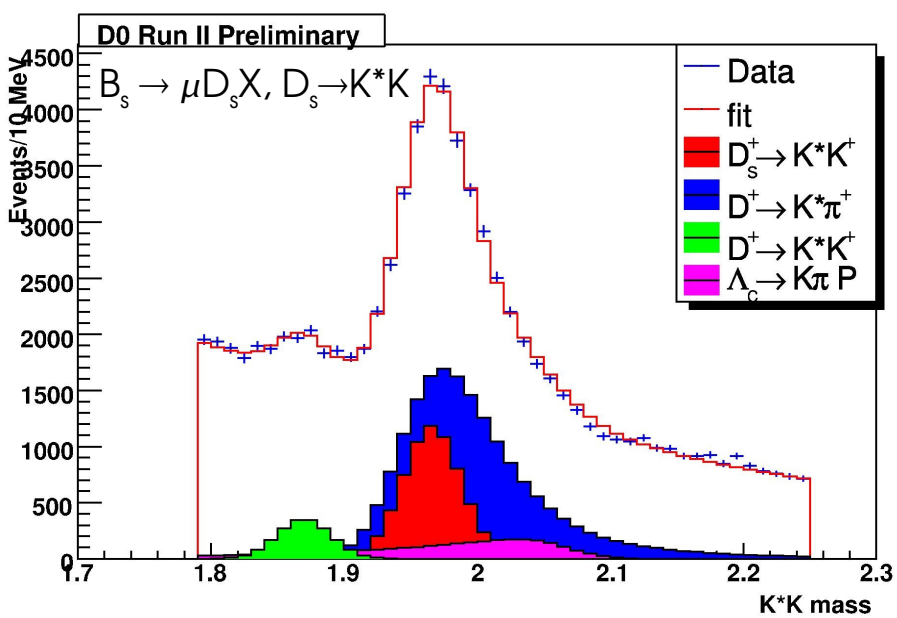
DØ B_s samples

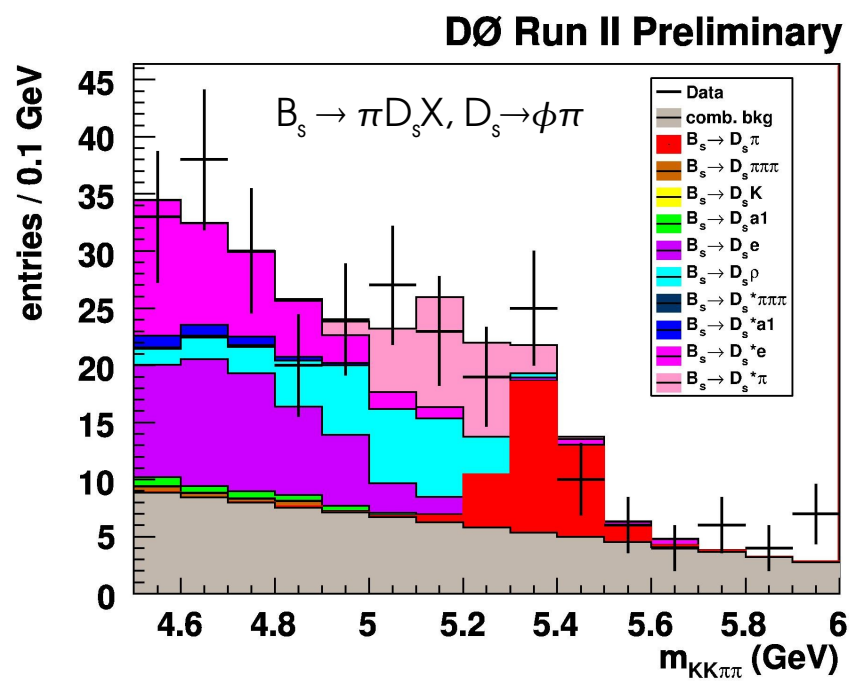
- 2.4 (1.1+1.3) fb^{-1} collected with inclusive single muon and dimuon triggers;
- semileptonic and hadronic signal samples selected with a likelihood ratio method:

channel	yield
$B_s \to \mu^+ D_s^- X$, $D_s^- \to \phi\pi^-$, $\phi \to K^+K^-$	44777
$B_s \to \mu^+ D_s^- X$, $D_s^- \to K^{*0}K^-$, $K^{*0} \to K^+\pi^-$	18098
$B_s \to e^+ D_s^- X$, $D_s^- \to \phi\pi^-$, $\phi \to K^+K^-$	1663
$B_s \to \pi^+ D_s^- X$, $D_s^- \to \phi\pi^-$, $\phi \to K^+K^-$	249
TOTAL	64787

all candidates are muon tagged





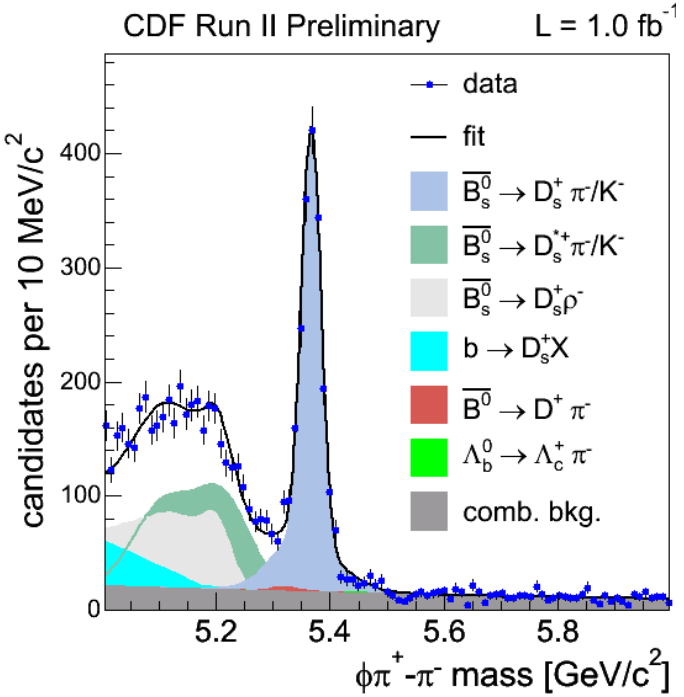


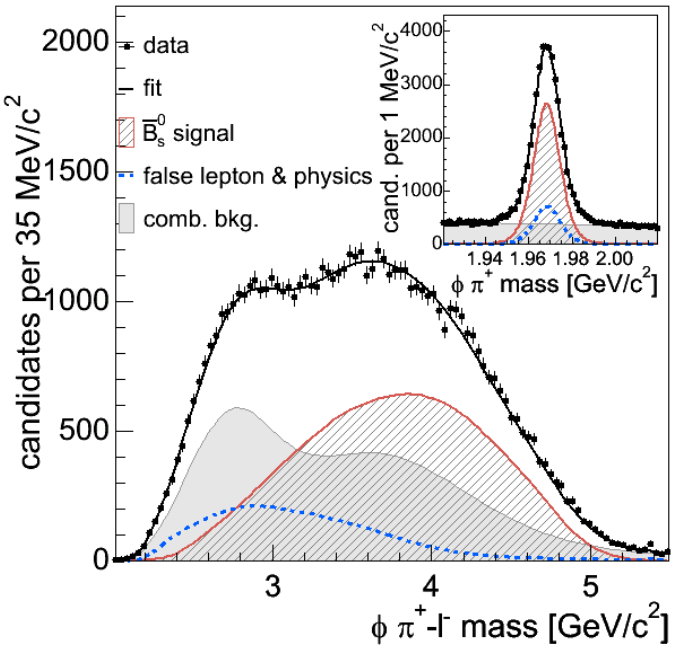
CDF B_s samples

- 1 fb^{-1} collected with displaced track trigger;
- hadronic and semileptonic signal samples: NN selection.

channel	yield
$B_s \to D_s^- \pi^+$, $D_s^- \to \phi\pi^-$, $\phi \to K^+K^-$	2000
$B_s \to D_s^{*-} \pi^+$, $D_s^{*-} \to D_s^- \gamma/\pi^0$ and $B_s \to D_s^- \rho^+$, $\rho^+ \to \pi^+\pi^0$	3100
$B_s \to D_s^- \pi^+$, $D_s^- \to K^{*0} K^-$, $K^{*0} \to K^+\pi^-$	1400
$B_s \to D_s^- \pi^+$, $D_s^- \to \pi^-\pi^+\pi^-$	700
$B_s \to D_s^- \pi^+\pi^-\pi^+$, $D_s^- \to \phi\pi^-$, $\phi \to K^+K^-$	700
$B_s \to D_s^- \pi^+\pi^-\pi^+$, $D_s^- \to K^{*0} K^-$, $K^{*0} \to K^+\pi^-$	600
$B_s \to D_s^- \pi^+\pi^-\pi^+$, $D_s^- \to \pi^-\pi^+\pi^-$	200
TOTAL	**8700**

channel	yield
$B_s \to \ell^+ D_s^- X$, $D_s^- \to \phi\pi^-$, $\phi \to K^+K^-$	29600
$B_s \to \ell^+ D_s^- X$, $D_s^- \to K^{*0} K^-$, $K^{*0} \to K^+\pi^-$	22000
$B_s \to \ell^+ D_s^- X$, $D_s^- \to \pi^-\pi^+\pi^-$	9900
TOTAL	**61500**





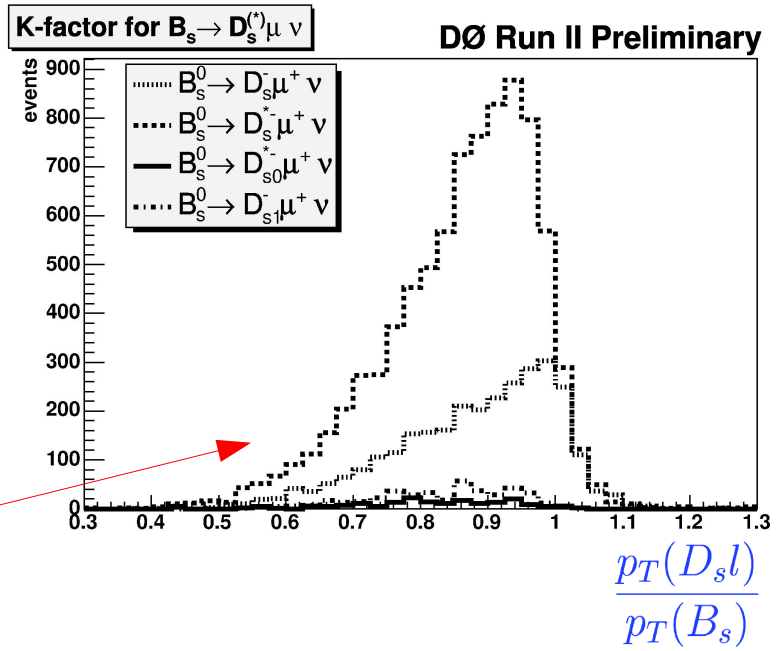
Proper decay time resolution

- Reconstructed decay time in B_s rest frame:
  - fully reconstructed decays:

$$ct = L_{xy}\frac{m_{B_s}}{p_T(B_s)}$$

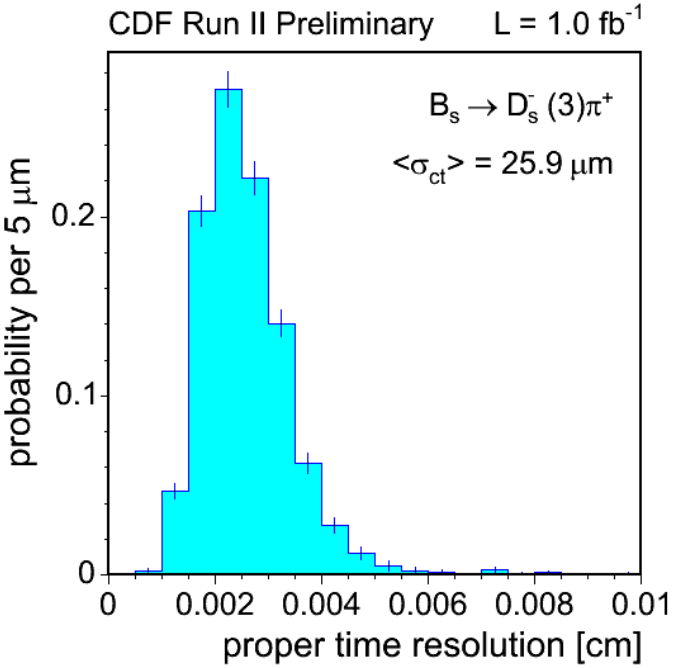
  - partially reconstructed decays:

$$ct = L_{xy}\frac{m_{B_s}}{p_T(D_s l)}k$$



- To enhance proper decay time resolution both experiments exploit Si layer close to beampipe (~1.5 cm) and use event-based σ_{ct}:

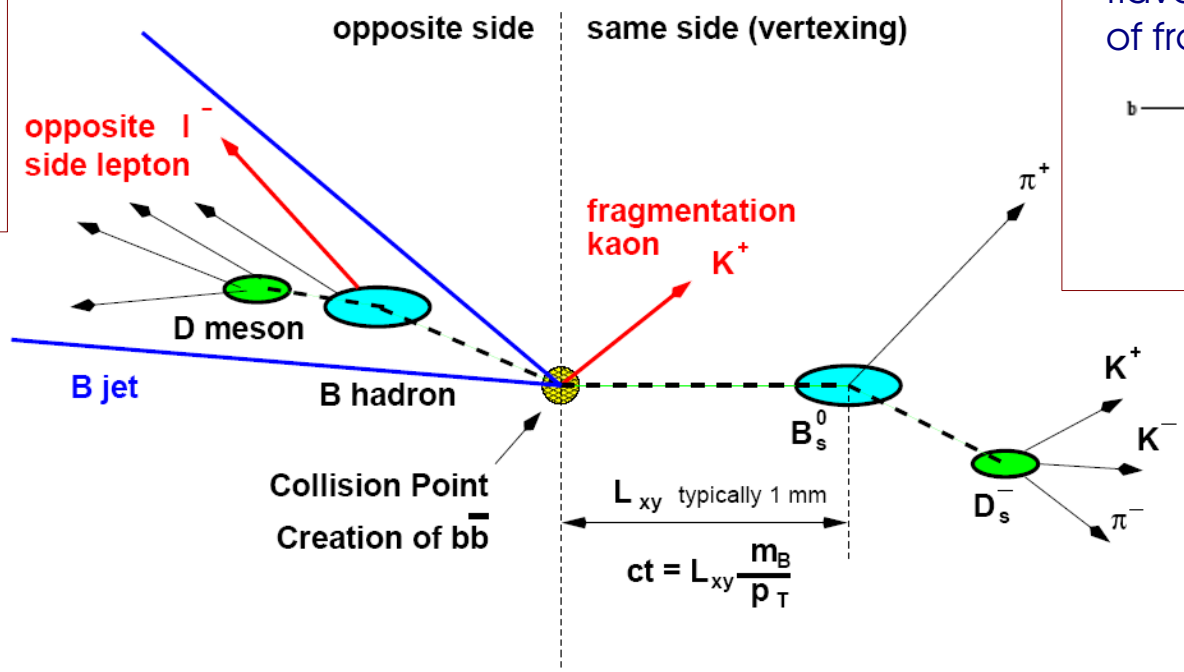
	channel	average resolution
CDF	had. fully rec.	26 μm
	had. part. rec.	29 μm
	semilep.	45 μm
DØ	w/ L0 Si layer	48 μm
	w/o L0 Si layer	65 μm



B_s production flavor tagging

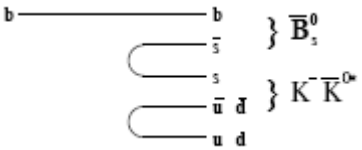
Opposite side taggers:

- lepton charge:
  $b \to \ell^- X$, but $b \to c \to \ell^+ X$
- jet charge: momentum weighted charge
- K charge:
  $b \to c \to K^- X$



Same side tagger:

- correlation between B_s flavor and the charge of fragmentation K



CDF:

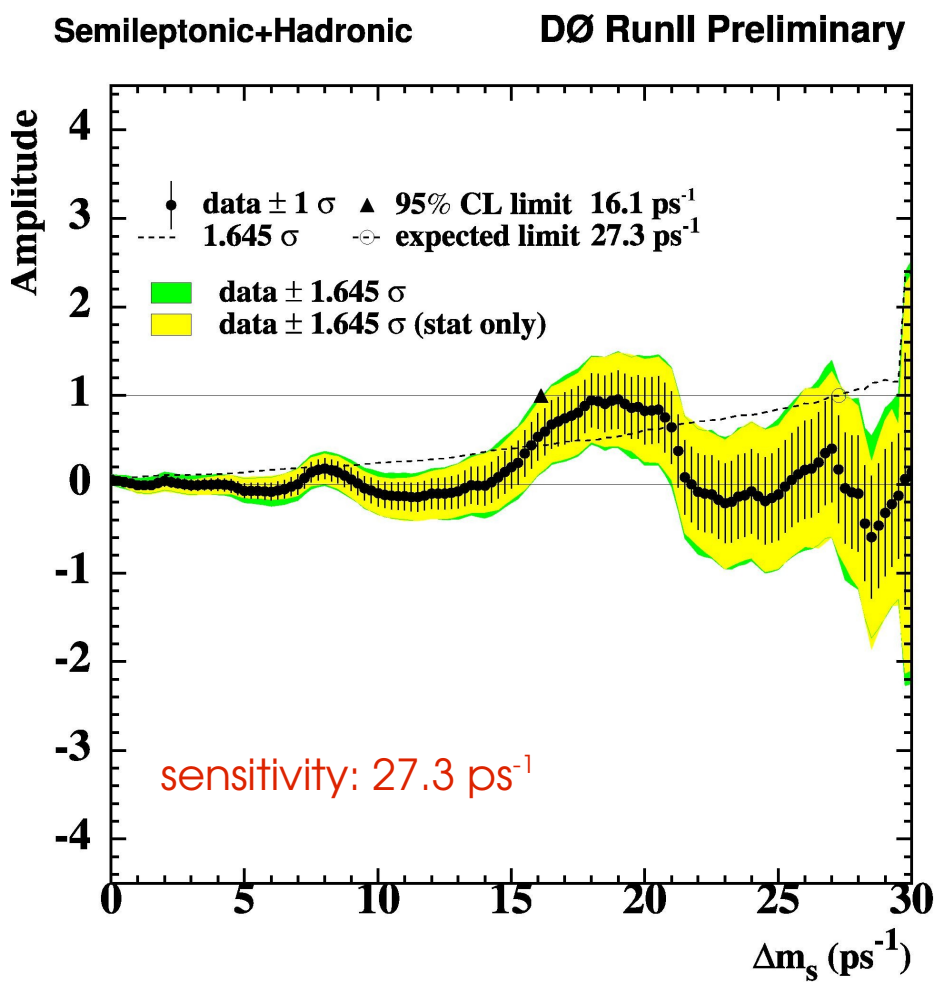
- NN combination of opposite side jet charge, kaon and lepton tags:
  $\varepsilon D^2 = 1.8\%$;
- NN kinematic and PID variables for same side kaon tag:
  $\varepsilon D^2 = 3.7\%$ (had.), 4.8% (semilep.).

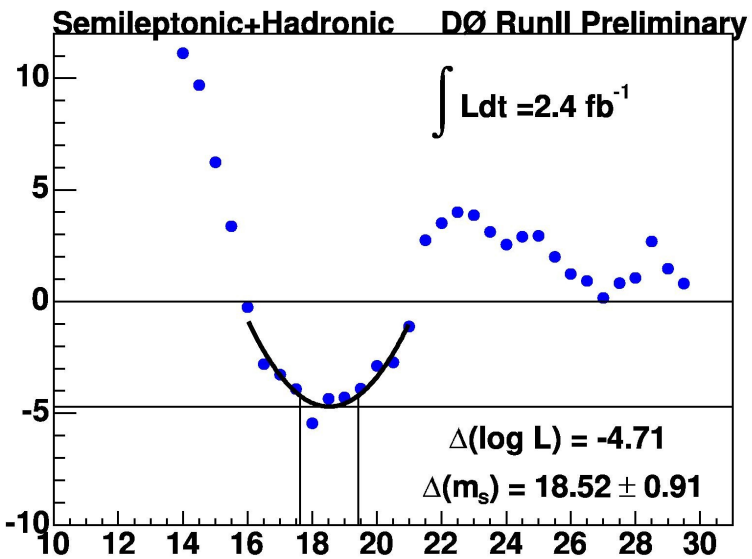
DØ:

- opposite side tagging uses lepton information or secondary vertex:
  $\varepsilon D^2 = 2.5\%$;
- combined single and multi-track tag:
  $\varepsilon D^2 = 4.5\%$.

New DØ result

- Amplitude scan technique is used to search for a significant signal.



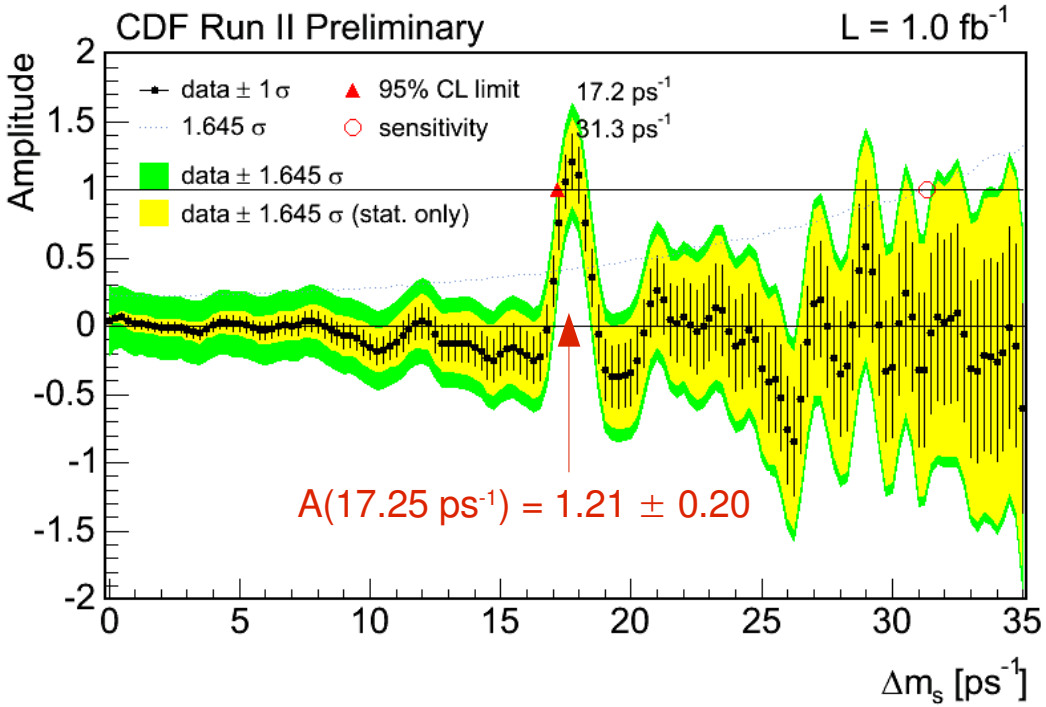


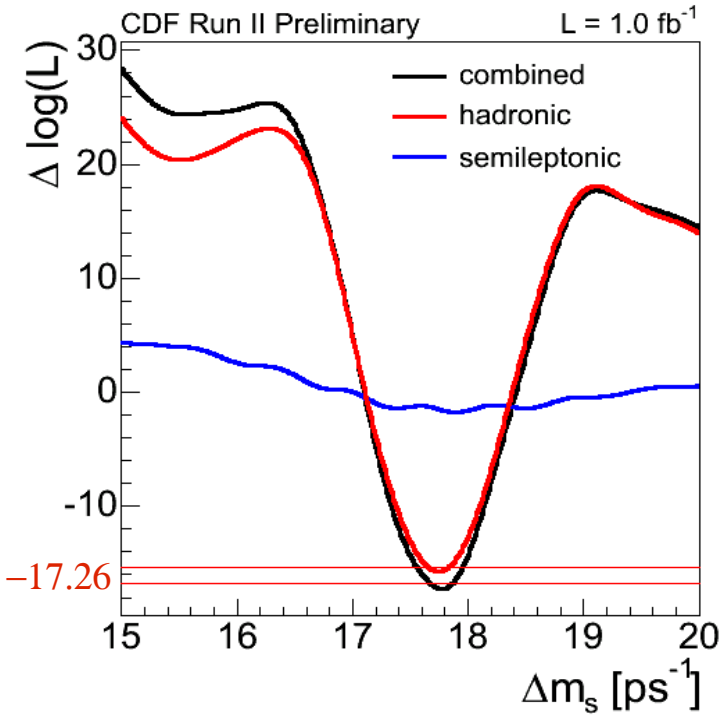
- A parabolic fit to the likelihood scan for Δm_s returns:

$$\Delta m_s = 18.56 \pm 0.87 \text{ ps}^{-1}$$

- 3.1σ statistical significance.

CDF results





$$\Delta m_s = 17.77 \pm 0.10\ (\text{stat}) \pm 0.07\ (\text{syst})\ \text{ps}^{-1}$$

- 5.4σ statistical significance.
- From $\dfrac{\Delta m_s}{\Delta m_d} = \dfrac{m_{B_s}}{m_{B_d}} \xi^2 \dfrac{|V_{ts}|^2}{|V_{td}|^2}$:

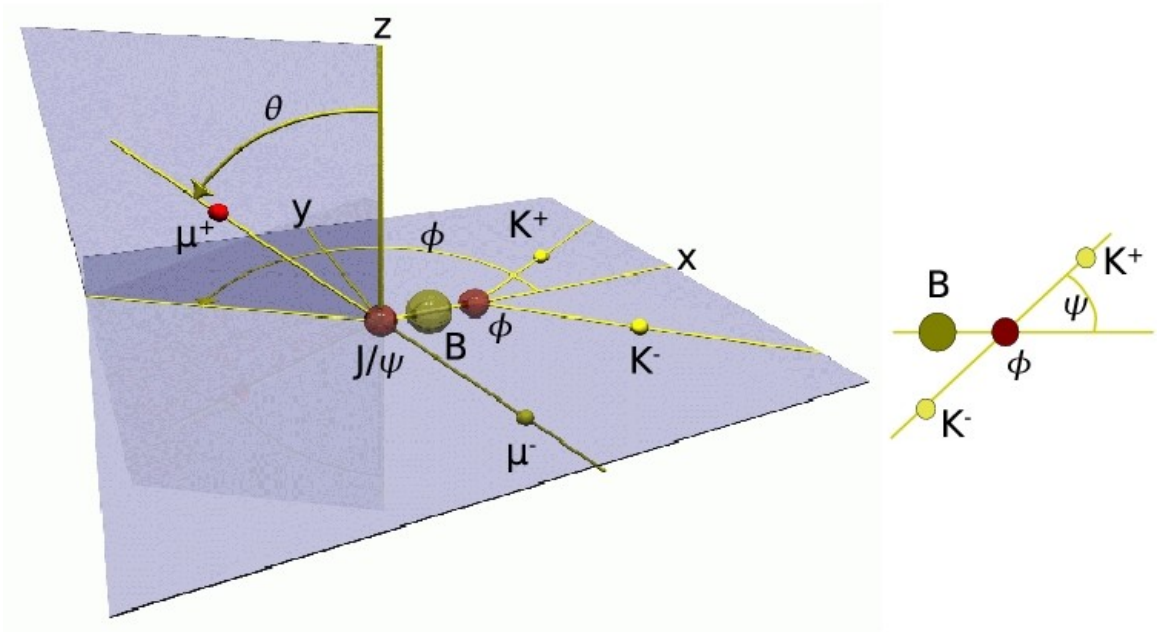
$$|V_{td}| / |V_{ts}| = 0.2060 \pm 0.0007(\text{exp})\ ^{+0.0081}_{-0.0060}\ (\text{theor})$$

CDF PRL 97, 242003 (2006)

Γ_s, $\Delta\Gamma_s$ and ϕ_s

$\Delta\Gamma_s$ analysis overview

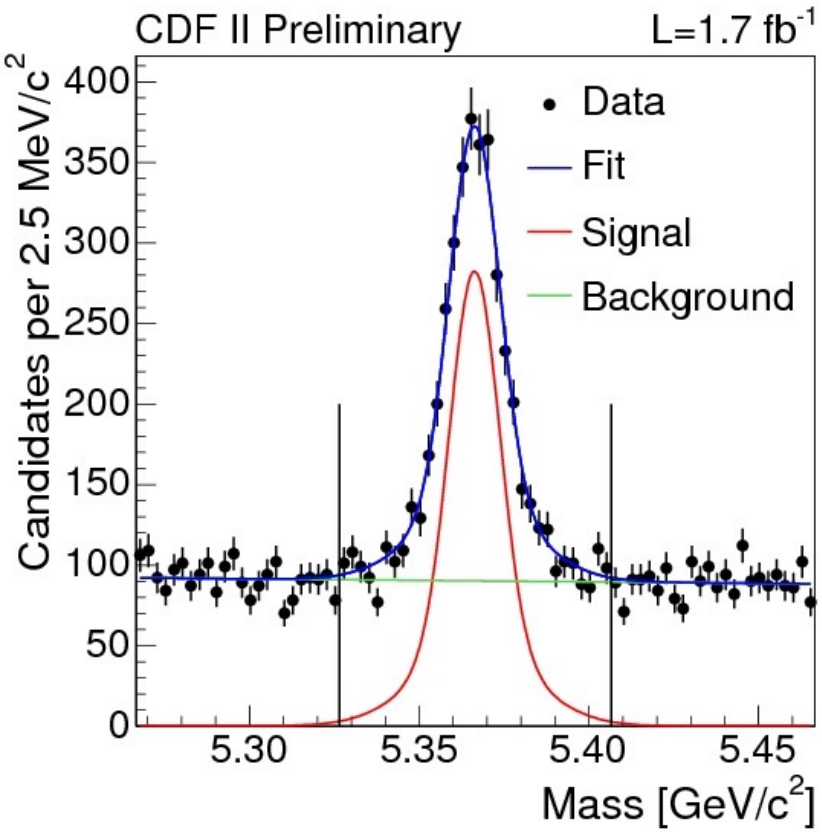
- The decay mode $B_s \to J/\psi\phi$ is sensitive to $\Delta\Gamma_s$ since it allows to disentangle the heavy (B_{sH}) and the light (B_{sL}) B_s mass eigenstates:
  - $B_s \to J/\psi\phi$ is a $P \to VV$ decay, the final state can have L=0,2 (CP-even) or L=1 (CP-odd);
  - for $\phi_s \simeq 0$, B_{sH} is CP-odd and B_{sL} is CP-even;
  - a time-dependent angular analysis of the $B_s \to J/\psi\phi$ decay products can distinguish between the B_s mass eigenstates.
- Since $\Delta\Gamma_s$ is expected to be large there is also sensitivity to the mixing phase ϕ_s.

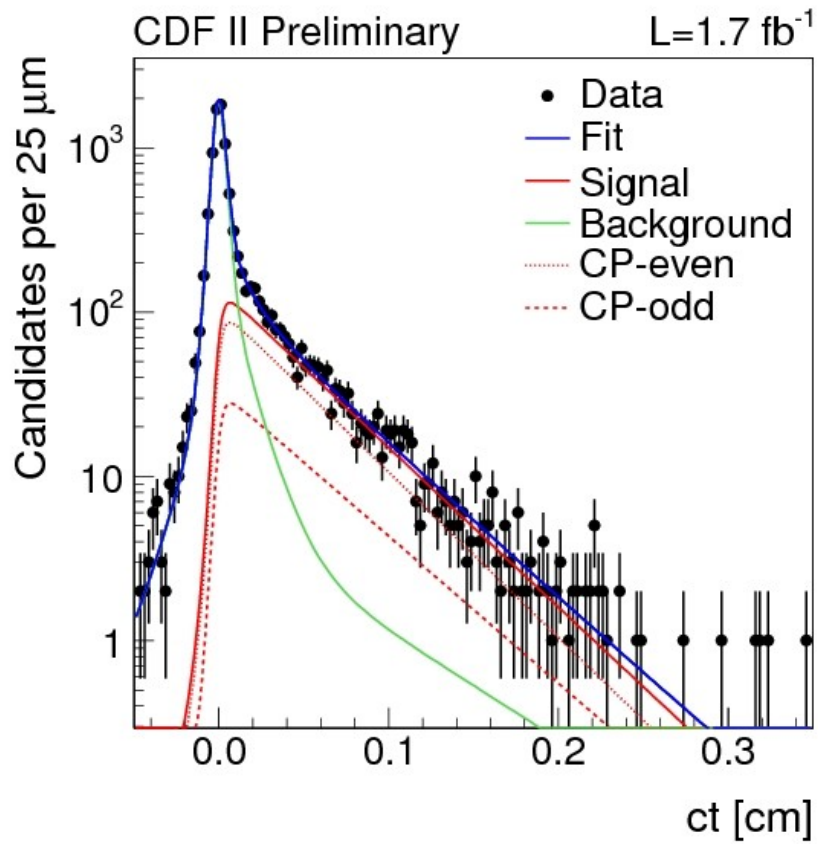


New CDF $\Delta\Gamma_s$ measurement

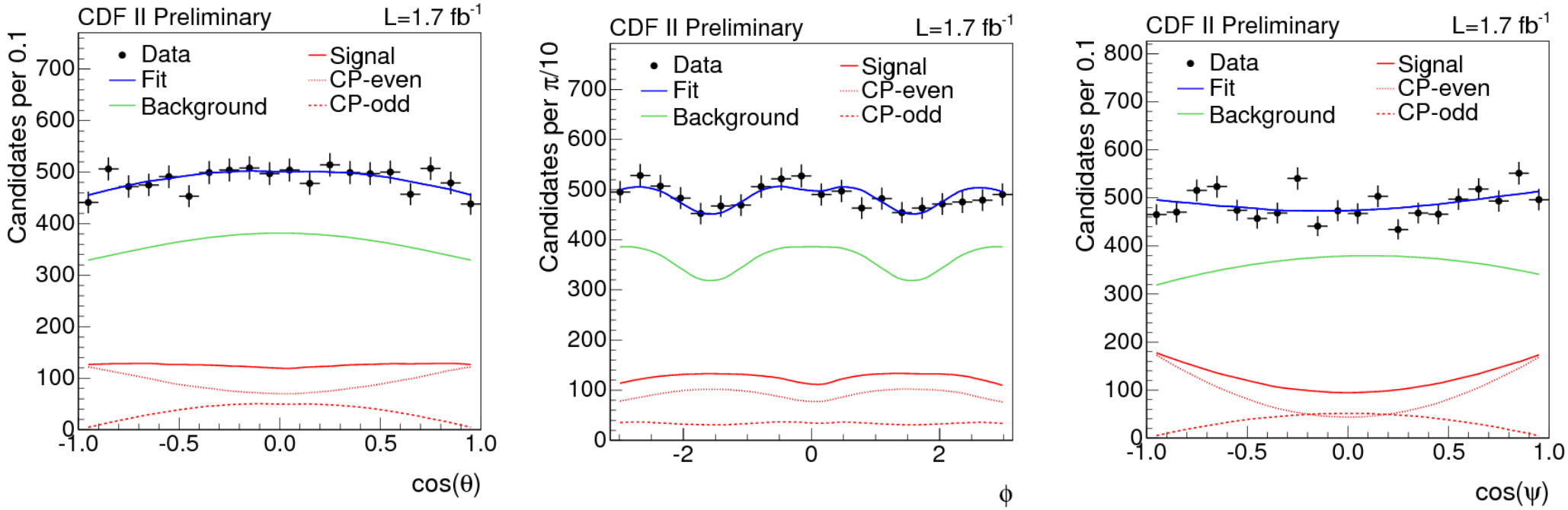
- 1.7 fb^{-1} collected by dimuon trigger;
- $B_s \to J/\psi\phi$ is reconstructed in the final state $J/\psi \to \mu^+\mu^-$ and $\phi \to K^+K^-$;
- loose kinematic preselection and NN improved selection yield 2500 $B_s \to J/\psi\phi$ candidates.

$$ct = L_{xy}\frac{m_{B_s}}{p_T(B_s)}$$





New CDF $\Delta\Gamma_s$ result



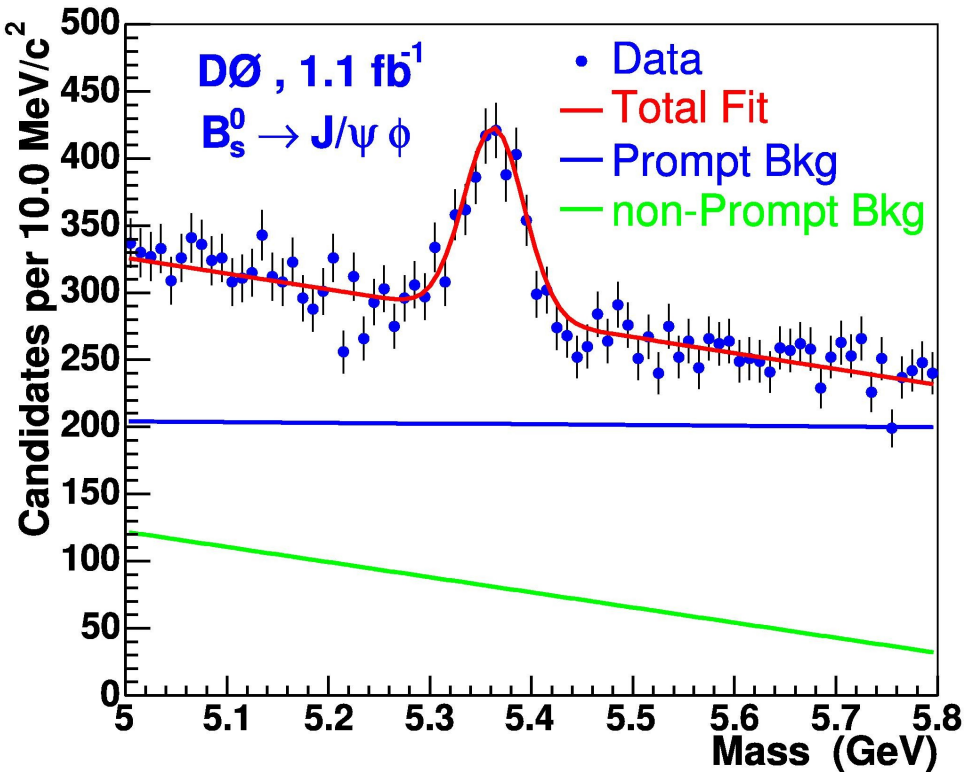
- Under the hypothesis $\phi_s = 0$, a multivariate unbinned Maximum-Likelihood fit (mass, lifetime, angles) returns:

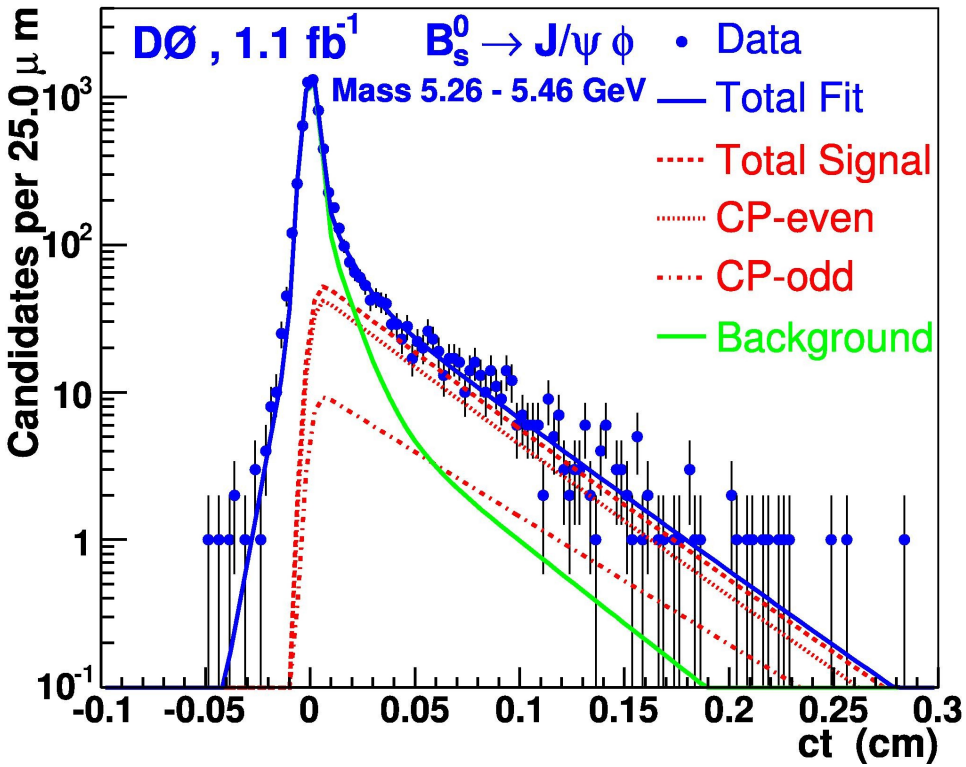
$$c\tau_s = 456 \pm 13\ (\text{stat}) \pm 7\ (\text{syst})\ \mu\text{m}$$

$$\Delta\Gamma_s = 0.076\ ^{+0.059}_{-0.063}\ (\text{stat}) \pm 0.006\ (\text{syst})\ \text{ps}^{-1}$$

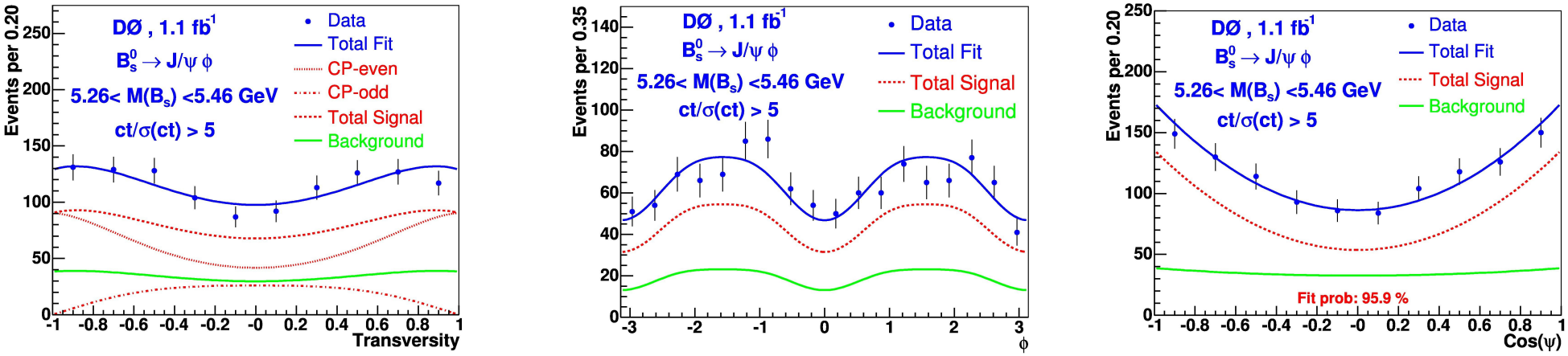
DØ $\Delta\Gamma_s$ measurement

- 1.1 fb^{-1} collected by dimuon trigger;
- $B_s \to J/\psi\phi$ is reconstructed in the final state $J/\psi \to \mu^+\mu^-$ and $\phi \to K^+K^-$;
- kinematic selection: 1040 $B_s \to J/\psi\phi$ candidates;
- multi-variable unbinned Maximum-Likelihood fit: mass, lifetime, angles.





DØ $\Delta\Gamma_s$ result



- Under the hypothesis $\phi_s = 0$:

$$c\tau_s = 456 \pm 24\ (\text{stat})\ ^{+3}_{-9}\ (\text{syst})\ \mu\text{m}$$

$$\Delta\Gamma_s = 0.12\ ^{+0.08}_{-0.10}\ (\text{stat}) \pm 0.02\ (\text{syst})\ \text{ps}^{-1}$$

- Allowing ϕ_s to float in the fit:

$$\Delta\Gamma_s = 0.17 \pm 0.09\ (\text{stat}) \pm 0.02\ (\text{syst})\ \text{ps}^{-1}$$

$$\phi_s = -0.79 \pm 0.56\ (\text{stat})\ ^{+0.14}_{-0.01}\ (\text{syst})$$

DØ PRL 98, 121801 (2007)

New DØ $\Delta\Gamma_s$ constrained fit

- DØ repeated the fit of $B_s \to J/\psi\phi$ data with two constraints on Γ_s, $\Delta\Gamma_s$, and ϕ_s:
  - from flavor-specific decay lifetime:

$$\Gamma_{\rm fs} = \Gamma_s - \frac{(\Delta\Gamma_s)^2}{2\,\Gamma_s} + \mathcal{O}\left(\frac{(\Delta\Gamma_s)^3}{\Gamma_s^2}\right)$$

$1/\Gamma_{fs}$ from world average (1.440±0.036 ps);

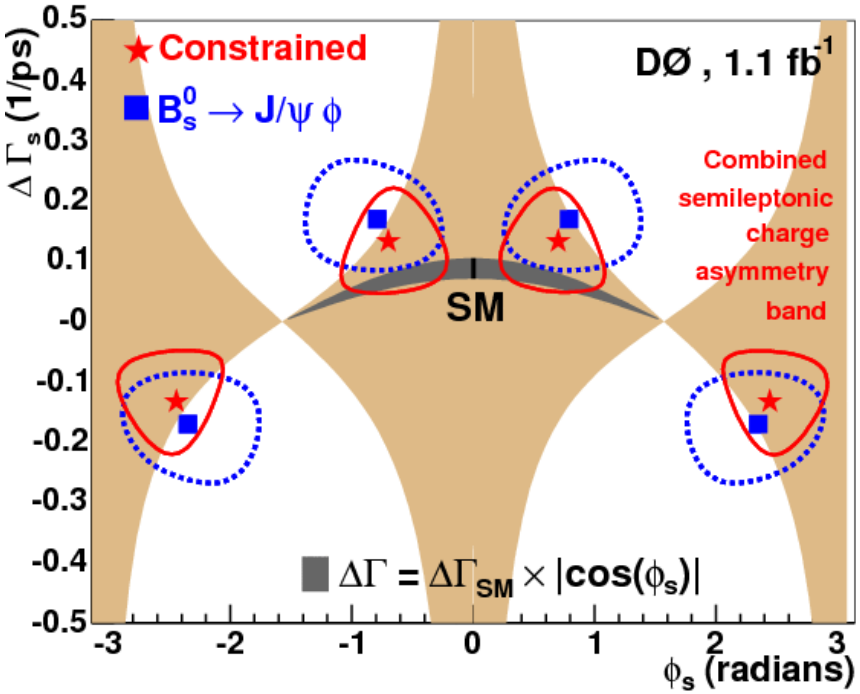
  - from the B_s semileptonic charge asymmetry:

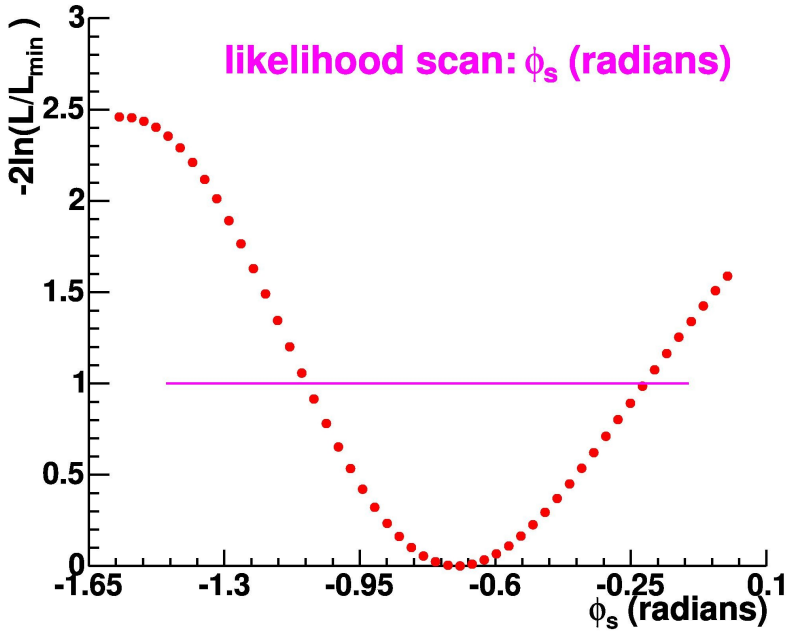
$$A^s_{SL} = \frac{N(\bar{B}^0_s \to \ell^+ X) - N(B^0_s \to \ell^- X)}{N(\bar{B}^0_s \to \ell^+ X) + N(B^0_s \to \ell^- X)} = \frac{\Delta\Gamma_s}{\Delta m_s}\tan\phi_s$$

using A_{SL} = 0.0001±0.0090 from the combination of the same-sign inclusive dimuon charge asymmetry (DØ Phys. Rev. D74, 092001 (2006)), the $B_s \to \mu\nu D_s$ (DØ PRL 98, 151801 (2007)), and Δm_s from CDF (CDF PRL 97, 242003 (2006)):

$$\Delta\Gamma_s \cdot \tan\phi_s = A^s_{SL} \cdot \Delta M_s = 0.02 \pm 0.16\ \mathrm{ps}^{-1}$$

DØ constrained fit result

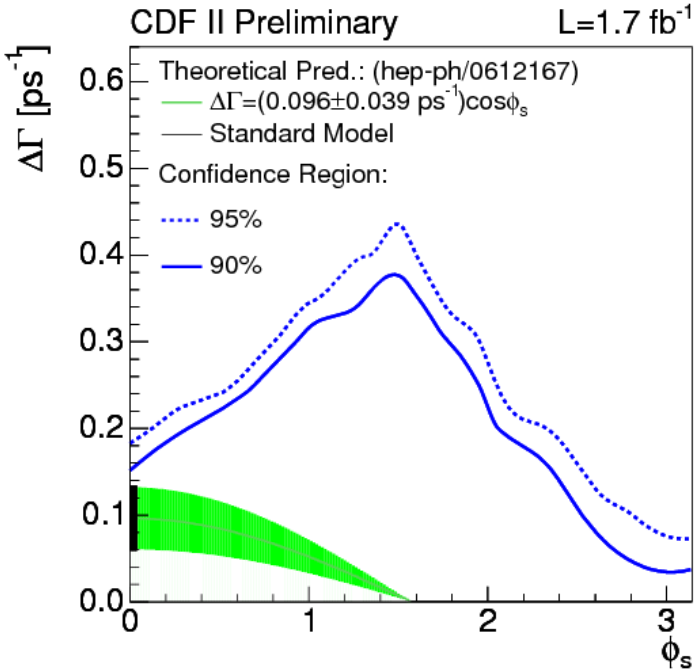




- The constrained fit returns:

$$\Delta\Gamma_s = 0.13 \pm 0.09\ \mathrm{ps}^{-1}$$

$$\phi_s = -0.70\ ^{+0.47}_{-0.39}$$



Summary

- A new generation of fb^{-1}-size analyses by the CDF and DØ Collaborations has started to give unprecedented insights into the nature of B_s-$\bar{B}_s$ system:
  - Δm_s: CDF: $17.77 \pm 0.10 \pm 0.07\ ps^{-1}$; DØ: $18.56 \pm 0.89\ ps^{-1}$
  - $\Delta\Gamma_s$: CDF: $0.076\ ^{+0.059}_{-0.063} \pm 0.006\ ps^{-1}$; DØ: $0.13 \pm 0.09\ ps^{-1}$
  - ϕ_s: DØ: $-0.70\ ^{+0.47}_{-0.39}$
- Tagged ϕ_s analysis under way, stay tuned for winter conferences.
- This is just the beginning. 6-7 fb^{-1} are expected by 2009 and more accurate and precise results are around the corner.

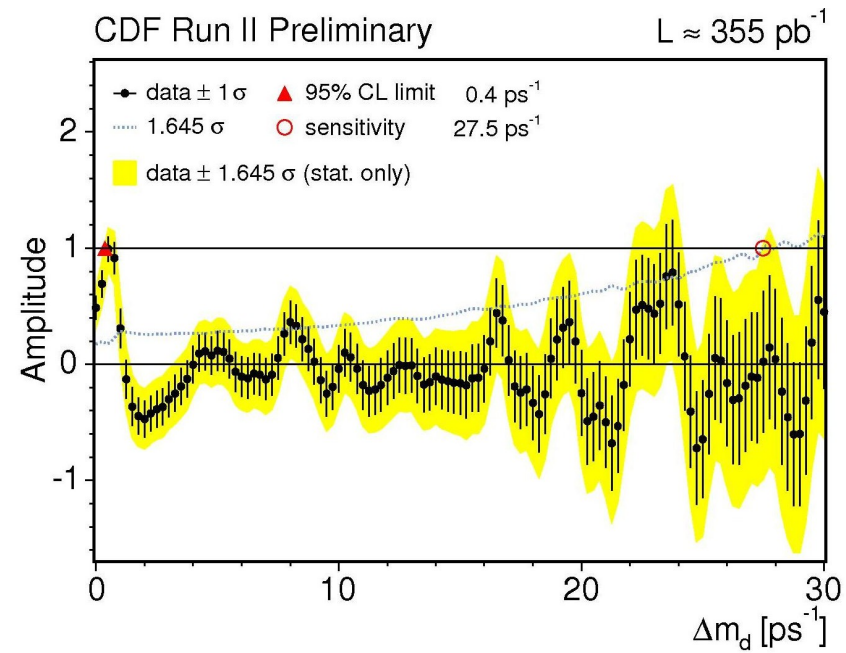
Back-up slides

Amplitude scan technique

- "Classic" method for B_s oscillations searches:
  - same properties as a Fourier analysis;
  - based on a Maximum-Likelihood fit;
  - sets directly a limit if no signal is found;
  - allows a simple combination of results from different experiments.

- Technique:
  - introduce an oscillation amplitude A into the proper time distribution:
    $$P(t) \approx (1 \pm A\, D \cos(\Delta m_s\, t))\, \exp(-t/\tau);$$
  - maximum-likelihood fits of A for fixed Δm_s values;
  - ideal case: A=1 for the correct Δm_s, A=0 otherwise;
  - signal evidence: Δm_s for which A is compatible with 1.

B_d oscillations example



- points: $A \pm \sigma_A$ from ML fits with fixed Δm_d
- yellow band: $A \pm 1.645\, \sigma_A$
- dotted curve: $1.645\, \sigma_A$ vs Δm_d
- Δm_d values for which $A + 1.645\, \sigma_A < 1$ are excluded with 95% C.L.
- analysis sensitivity: Δm_d for which $1.645\, \sigma_A = 1$

H.G.Moser and A.Roussarie, NIM A384 (1997) 491-505

$\Delta\Gamma_s$ fit

$$\frac{d^4P(\vec{\omega},t)}{d\vec{\omega}dt} \propto |A_0|^2 f_1(\vec{\omega})\mathcal{T}_+ + |A_{||}|^2 f_2(\vec{\omega})\mathcal{T}_+$$
$$+ |A_\perp|^2 f_3(\vec{\omega})\mathcal{T}_- + |A_0||A_{||}| f_5(\vec{\omega})\cos(\delta_{||})\mathcal{T}_+$$
$$+ |A_{||}||A_\perp| f_4(\vec{\omega})\cos(\delta_\perp - \delta_{||})\sin\phi_s(e^{-\Gamma_H t} - e^{-\Gamma_L t})/2$$
$$+ |A_0||A_\perp| f_6(\vec{\omega})\cos(\delta_\perp)\sin\phi_s(e^{-\Gamma_H t} - e^{-\Gamma_L t})/2$$

where

$$\mathcal{T}_\pm = ((1 \pm \cos\phi_s)e^{-\Gamma_L t} + (1 \mp \cos\phi_s)e^{-\Gamma_H t})/2$$

$$f_1(\vec{\omega}) = \frac{9}{32\pi} 2\cos^2\psi(1 - \sin^2\theta\cos^2\phi)$$
$$f_2(\vec{\omega}) = \frac{9}{32\pi}\sin^2\psi(1 - \sin^2\theta\sin^2\phi)$$
$$f_3(\vec{\omega}) = \frac{9}{32\pi}\sin^2\psi\sin^2\theta$$
$$f_4(\vec{\omega}) = -\frac{9}{32\pi}\sin^2\psi\sin 2\theta\sin\phi$$
$$f_5(\vec{\omega}) = \frac{9}{32\pi}\frac{1}{\sqrt{2}}\sin 2\psi\sin^2\theta\sin 2\phi$$
$$f_6(\vec{\omega}) = \frac{9}{32\pi}\frac{1}{\sqrt{2}}\sin 2\psi\sin 2\theta\cos\phi$$